Integral Bridges and the Modeling of Soil-Structure Interaction

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Introduction
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About soil-structure interaction

Fig. 6.21  Cantilever sheet pile wall.
About soil-structure interaction

Wall movement $\Delta / \text{Height } H$

Passive Movement

Active Movement

$K_p$

$K_0$

$K_a$
Seasonal changes
Seasonal changes

Pressures increase every year for 100-200 cycles

For design, consider maximum and minimum pressures
Analysis methods

1. Limiting equilibrium approach
2. Soil-structure interaction (continuum)
3. Soil-structure interaction (springs)
1 – Limiting equilibrium

Full height integral abutment on pad footing

Full height integral abutment on piles

Bank pad
1 – Limiting equilibrium

Figure 5 Earth pressure distributions for abutments which accommodate thermal expansion by rotation and/or flexure
1 – Limiting equilibrium

Full height integral abutment on pad footing

Full height integral abutment on piles

Bank pad

\[ K^* = K_o + \left( \frac{Cd'd}{H} \right)^{0.6} K_{p;t} \]

\[ C = 0.51E_s + 14.9 \text{ but } 20 \leq C \leq 66 \quad (E_s \text{ in MPa}) \]
1 – Limiting equilibrium
Structural idealisation

- Shell elements
  - Shear, bending, twisting and in-plane forces
Structural idealisation

3D beam elements (girders)

Straight girders, Precast etc

Shell elements (slab)
Structural idealisation

- Skew or curved etc

Shell elements
  - (web)

Shell elements
  - (slab)

3D beam elements
  - (bracing)

3D beam elements
  - (flanges & stiffeners)
Structural idealisation

Y

Z X
Grid models

“The conventional 2D-grid models used in current practice
• Substantially underestimate the girder torsional stiffnesses in I-girder bridges
• Substantially misrepresent the cross-frame responses
• Do not address the calculation of girder flange lateral bending in skewed I-girder bridges”

Section 2.9
“...difficulties arise when in-plane effects are considered... the real problem is the occurrence of local in-plane distortions of the grillage members... which are clearly inconsistent with the behaviour of the bridge deck.”

Section 7.5
1 – Limiting equilibrium

Shell elements (slabs)
K* approach not adequate

Embedded wall
integral abutment

Full height integral abutment
on single row of piles

Bank pad on single row of piles
Material Key
- Weald clay
- Tilgate
- Sands
- Limestone
- Concrete

2D Beam elements

Check extents

Plane strain elements
Mesh checks

1. Width & depth of soil block
2. Element shapes and aspect ratios
   - Avoid angles <30°
   - 1:1 ideal
   - 1:3 max (areas of interest)
   - 1:10 max (remote)
3. Mesh refinement
4. Element formulation – quadratic better

**Need automatic re-meshing**
2 – SSI with soil continuum

Check shape & refinement

Check extents

2D Beam elements

Material Key
- Weald clay
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Plane strain elements
Vertical stress at 10m depth
\[ S_Y = \rho g H = 1.8 \times -9.81 \times 10 = -176.58 \text{kPa} \]

Initial lateral stress at 10m depth
\[ S_X = S_Z = K_0 \times S_Y \text{ where } K_0 = 0.5 \, (\phi' = 30\degree) \]
\[ = 0.5 \times -176.58 = -88.29 \text{kPa} \]

Maximum (final) lateral stress at 10m depth
\[ S_X = S_Z = K_p \times S_Y \text{ where } K_p = \frac{1 + \sin \phi'}{1 - \sin \phi'} = 3.0 \]
\[ = 3.0 \times -176.58 = -529.74 \text{kPa} \]
Analysis: Analysis 3
Loadcase: 1:Loadcase 1 (Copy 2), Increment 1
Results file: e201Fr1 SI test soil block (Mohr-Coulomb)~Analysis 3.mys
Entity: Stress - Plane Strain
Component: SX (Units: kN/m²)

Maximum: 1.09884E-9 at node 349
Minimum: -88.29 at node 1
2 – SSI with soil continuum

Material Key
- Weald clay
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Check shape & refinement

2D Beam elements

Check extents

Mohr-Coulomb material

Plane strain elements
2 – SSI with soil continuum

- **Cohesive soils**
  - Strain ratcheting may be ignored

- **Granular soils**
  - Use modified elastic modulus
  - Based on K* equations
  - Determine effective height, H, iteratively
Check shape & refinement

Check extents

2D Beam elements

Modified elastic modulus*

Mohr-Coulomb material

Plane strain elements

Material Key
- Weald clay
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2 – SSI with soil continuum

• Interface between soil and structure
  – Joint elements
  – Contact slidelines
  – Elasto-plastic interface materials

• Back of wall friction angle, $\delta$
  – Maximum $\delta=\varphi'$
  – Smooth $\delta=0$
  – Suggested $\delta=\varphi'/2$
Frictional interface \( \delta = \phi' / 2 \)

2D Beam elements

Check shape & refinement

Check extents

Plane strain elements

Modified elastic modulus*

Mohr-Coulomb material

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Embedded wall integral abutment

Continuum

Full height integral abutment on single row of piles

Soil modeled with nonlinear springs

Bank pad on single row of piles

Discrete piles

K* approach not adequate
3 – SSI with soil springs

Deck (shells/ 3D beams)

Ka and K* pressures

Soil springs / nonlinear joints

End screens (shells/ 3D beams)

Piles (3D beams)
3 – SSI with soil springs
3 – SSI with soil springs

Soil springs

End screens shells & 3D beams

Deck shells & 3D beams

Piles 3D beams
3 – SSI with soil springs

\[ k_h = A + Bz^\kappa \]

- \( \kappa = 0 \) for cohesive soil under moderate loads
- \( \kappa = 0.5 \) for medium cohesive soil and non-cohesive soil above water table
- \( \kappa = 1.0 \) for non-cohesive soil below the groundwater level or under greater loads
- \( \kappa = 1.5-2.0 \) for loose non-cohesive soil under very high loads
3 – SSI with soil springs

- Stiffer, stronger
- Soft, weaker

Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms—Working Stress Design
3 – SSI with soil springs

Lateral pressure $\sigma$

Passive Movement

$\sigma'_a$

$\sigma'_0$

Active Movement

$\sigma'_p$

Horizontal deflection

$k_h$

$\sigma$
3 – SSI with soil springs
Software requirements

• Structural elements (beams, shells)
• Geotechnical elements (joints, springs, continuum)
• Automatic remeshing
• Nonlinear materials (e.g. Mohr Coulomb)
• Easy way to vary properties with depth
\[ K* = K_0 + \left( \frac{C_d'd}{H} \right)^{0.6} K_{p,t} \]

Summary

Soil continuum

Soil Springs

UK Guidance: PD6694-1